Response to Anonymous Referee #2

Referee #2: In this manuscript, the author tried to explore the relationship between high-level anvil clouds and static stability through a novel approach known as estimated anvil-top stability (EAS), which is based on the minimum value of dθ/dz. The author claims that the upper-tropospheric stability (UTS) method, which relies on the lapse rate tropopause, underestimates the effect of stability on the anvil, while EAS provides a more accurate relationship. The findings further indicate that EAS has a stronger correlation with anvil clouds than UTS. This proposed method may be useful in understanding the factors that control cloud structure and composition. The topic of the research is interesting and the analysis results would be worth a concise publication. Though the manuscript is scientifically sound enough, the presentation style needs to be improved. Overall, the manuscript requires major revisions. I had the chance to read the comments of Anonymous Reviewer #2 and I do share all his/her general comments.

Response: We thank anonymous referee for reviewing our manuscript and very helpful comments to modify the manuscript. We have responded to all comments, and carefully improved the presentation of the manuscript accordingly.

Comments:

1. *What I can see as one of the major problems of the manuscript is that it lacks clarity in many places in its current form. Several sentences are not clear, please revise.*

   Response: The revised manuscript has been better reorganized with a brief introduction at the beginning of each section to help grasp the goal of analyses and to improve the clarity. More descriptions have been added to clarify the results.

   The manuscript has been better clarified and specified according to the following comments.

   Professional editing service has been pursued to guarantee an appropriate language use.

2. *Is it 3 km moving smoothing? What is the basis for selecting 3-km smoothing? What is the final vertical resolution of radiosonde data?*

   Response: Yes, it is 3-km moving smoothing. The selection of the smoothing window is empirical. The smoothing effects have been tested in König et al. (2019), which suggested that 3-km smoothing is well-behaved. The final vertical resolution is still 10 meters. This has been clarified in the revised manuscript.

3. *Is the LRT derived from this 3 km smoothed temperature profile as well? What is the reliability of the relationship established by the results obtained?*

   Response: Yes, the LRT is derived from the 3-km smoothed temperature profiles. As tested in König et al. (2019), 3-km smoothing will result in a bias no more than 500 m for the LRT. This has been clarified in the revised manuscript.

4. *The author may clearly describe how the Anvil cloud is categorized in this manuscript. What are the limitations of the MMCR for detecting the anvil clouds?*

Response: The MMCR is not sensitive to small ice crystals and is quickly attenuated by precipitation and optically thick clouds (Hollars et al., 2004). It means that the upper parts of thick clouds and thin cirrus clouds could be missed by the MMCR in Fig. 2. In comparison to the previous studies (Dessler et al., 2006; Berry and Mace, 2014; Hartmann and Berry, 2017), the ice cloud top height detected by the ground-based MMCR (shown in Fig. 2) is about 1-2 km lower than the cloud top height detected by the spaceborne lidar.

Nevertheless, the anvil top in this work just refers to the level of main convective outflows but not exactly the anvil top height. Thus, this missing upper parts of thick clouds and thin cirrus clouds may not influence our analyses, but do need further validation.

Thus, for the relationship between EAS and convective outflows, a further validation is presented in Fig. 3 (as shown below) on the basis of divergence profiles. The divergence profiles are derived from the EAR5 hourly reanalysis to collocate with the radiosonde observations. In Fig. 3, the divergence strength is inversely proportional to the EAS, and the height of the maximum divergence is close to but below the EAS height. This further supports the EAS constraint on the height and strength of convective outflows.

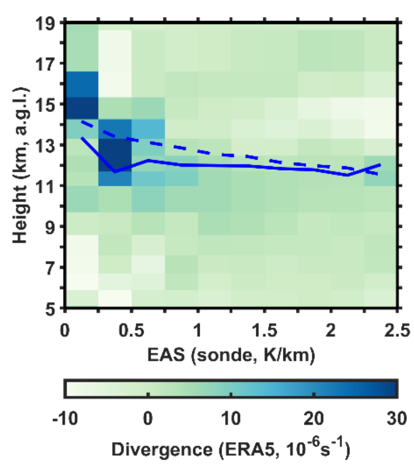


Figure 3. The composited divergence profiles of ERA5 against the EAS measured by radiosondes at the Manus site. The blue solid line indicates the mean level of the maximum divergence. The blue dashed line indicates the mean height of the dθ/dz minimum.

5. *What is the time frame for the ERA-5 data and other satellite measurements? Does it align with the radiosonde data from 2001 to 2011? The author should provide clarification on this matter.*

Response: In Sect. 4 of the revised manuscript (the Sect. 3 in the previous edition), only the Manus ground-based site during 2001-2011 is investigated. The hourly EAR5 data during the same period at the grid point of 147.5°E and 2.0°S are used. At this site, the MMCR is used to detect clouds and none of other satellite is used. This has been clarified in the main text.

In Sect. 5 of the revised manuscript, the satellite measurements and ERA5 data both in 2007 are used for investigating the relationship between global high clouds and stability. The EAR5 data has 1-hour and 0.5° resolutions. This has been clarified in the main text.

6. *Similarly, the author needs to provide the spatial gridding of each data set in the study. What is the spatial resolution for ERA-5, CERES, and DARDAR? While using multiple data sets of observation, reanalysis, and satellite data, it is suggested that it should be gridded to a uniform resolution for better comparison.*

Response: The CERES data has 1-hour and 1° resolution, centered at 0.5°, 1.5°, …. The ERA5 has 1-hour and 0.5° resolution. DARDAR provides instantaneous cloud profiles. For matching the EAR5 and CERES dataset, the ERA5 profiles are averaged to 1° resolution, centered at 0.5°, 1.5°, …. To collocate the EAR5 of 0.5° resolution and DARDAR datasets, the instantaneous DARDAR cloud profiles within 0.25° and half an hour of each ERA5 grid points are used to represent the cloud condition of the ERA5 grid point. This has been specified in the revised manuscript.

7. *What was the horizontal drift of the balloon while comparing the cloud fraction of MMCR?*

Response: Owing to the balloon drift, the mean horizontal distance between the balloon location and the MMCR at the cloud top height is 13.1 km.

8. *How are the lower-level thin cirrus ice crystals accounted for if the ice clouds are identified based on cloud top temperature?*

Response: As suggested in Krämer et al. (2016), thin in situ origin cirrus clouds are normally formed below -38℃ with slow updraft. But those thin cirrus clouds are not well identified by the MMCR, since the MMCR is not sensitive to small ice crystals. This uncertainty has been clarified in the main text of the revised manuscript.

Due to the limitation of the MMCR on detecting those thin cirrus clouds, a further validation has been added for the relationship between the EAS and ERA5-based divergence (please see the response to the comment #4). The focus of this paper is further clarified as: the EAS is a constraint on the strength and height of convective outflows, and thereby constrains high ice clouds related to convection.

9. *The methodology to estimate the moist adiabatic from observation and model datasets used in this study may be explained.*

Response: Moist adiabatic dθ/dz (Γ_m) is calculated from the radiosonde-observed temperature and pressure profiles as:

$$\Gamma_m\,(T,p) = \left(\frac{1000}{p}\right)^{\frac{R_a}{c_{pa}}} \cdot \frac{g}{c_{pa}}\left(1 - \frac{1+L_v q_s(T,p)/R_a T}{1+L_v^2 q_s(T,p)/c_{pa} R_v T^2}\right). \quad (7)$$

T and p are the radiosonde-detected temperature and pressure. R_a is the specific gas constant of dry air. R_v is the specific gas constant for water vapor. c_{pa} is the specific heat capacity for dry air at constant pressures. g is the gravitational acceleration. q_s is the saturated mass fraction of water vapor. L_v is the latent heat of vaporization.

This has been specified in the revised manuscript. In Fig. 2a, at each vertical level, the observed pressure and temperature were taken in to the Eq. (7) to compute moist adiabatic dθ/dz.

10. *The height of the minimum potential temperature gradient (**Fig. 4b**), commonly known as the convective outflow level or convective tropopause, has been extensively studied and documented by numerous researchers and needs to be included and discussed in the present study (see the reference).*

Response: Thank you for providing these references. They have been added and discussed in the main text: The EAS is the stability at the dynamical tropopause, which is the lower boundary of the TTL and corresponds to the height of convective outflows (Sunilkumar et al., 2013; Babu, 2024; Randel and Jensen, 2013); In Fig. 5b, the height of the EAS is about 10-13 km in the deep tropics, and is consistent with the radiosonde and GPS RO observations (Gettelman and Forster, 2002; Sunilkumar et al., 2017; Biondi et al., 2012; Sunilkumar et al., 2013; Xian and Fu, 2015; Babu, 2024).

Technical corrections:

The English language used in the manuscript needs to be checked by professionals who are native English speakers.

Response: Professional editing service has been used to improve the language use.

Line 28: "Cloud responses to the environmental changes have not been correctly simulated in models" may be rewritten avoiding concluding statements.

Response: It has been rewritten as: "Cloud responses to environmental changes have uncertainty in models".

Line 197: 'Nevertheless, the high-resolution radiosondes are limited at islands and coastal sites or during short-term field campaigns.' What about using the available high-resolution GNSS RO data? see the attached references.

Response: It has been revised as: "Observations from the Global Navigation Satellite System – Radio Occultation (GNSS-RO) and reanalysis are both available to pursue the general global and climate analyses. GNSS-RO observations can provide temperature profiles with the vertical resolution of 100 m for investigating the tropospheric and stratospheric thermal stratifications (Biondi et al., 2012; Sunilkumar et al., 2013; Xian and Fu, 2015; Ho et al., 2020; Babu, 2024). The reanalysis can provide atmospheric data with hourly resolution and covers a full period from 1940 to present (Hersbach et al., 2020), although the vertical resolution of the reanalysis is coarse."

Line 225: How is the ERA-5 data on pressure levels used to identify the height of LRT? Figure 1 The tick labels are missing on the y-axis.

Response: The ERA5 temperature, geopotential and divergence profiles are used in this work. θ is computed via temperature and pressure. The ERA5 dT/dz and $d\theta/dz$ profiles are computed from the ERA5 temperature and geopotential profiles at the half levels:

$$\frac{dT}{dz}_{i+1/2} = \frac{T_{i+1}-T_i}{z_{i+1}-z_i}, \quad (1)$$

$$\frac{d\theta}{dz}_{i+1/2} = \frac{\theta_{i+1}-\theta_i}{z_{i+1}-z_i}, \quad (2)$$

$$z_{i+1/2} = \frac{z_{i+1}+z_i}{2}, \quad (3)$$

where T, z and θ are the ERA5 temperature, geopotential height and potential temperature, respectively. The subscripts '$i+1$' and 'i' represent two adjacent levels in the ERA5 atmospheric profiles. The subscript '$i+1/2$' represents the gradient at the half level. The method of calculating the WMO LRT is consistent with that proposed in Reichler et al. (2003):

i. Linearly interpolate the profiles of $(dT/dz)_{i+1/2}$ and $(d\theta/dz)_{i+1/2}$ to obtain the continuous profiles of dT/dz and $d\theta/dz$ at the 100-m resolution;

ii. Search for the lowest half level of $-(dT/dz)_{i+1/2}$ less than 2 K/km above 5 km;

iii. Compute the mean of $-dT/dz$ for a 2-km deep layer above the half level that is located in the second step, and if it is greater than 2 K/km, repeat the second step to search upward further for the half level whose $-(dT/dz)_{i+1/2}$ is less than 2 K/km, until both of the criteria are fulfilled at the half level $j + 1/2$;

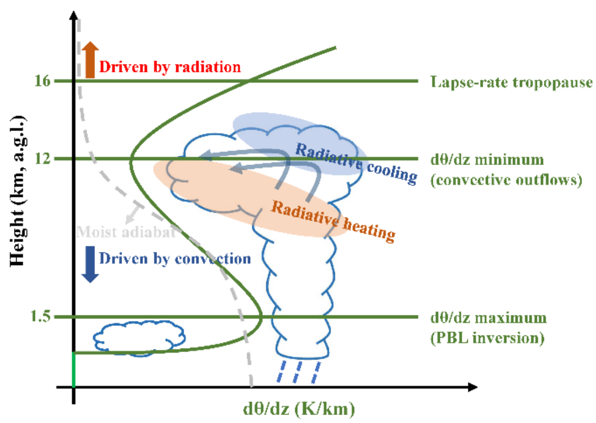
iv. Compute the exact position of the LRT between the levels of $j - 1/2$ and $j + 1/2$ via linear interpolation:

$$LRT = z_{j-1/2} + \frac{z_{j+1/2} - z_{j-1/2}}{dT/dz_{j+1/2} - dT/dz_{j-1/2}}(-2 - dT/dz_{j-1/2}). \quad (4)$$

Reichler et al. (2003) and Meng et al. (2021) reported that the root-mean-square errors of the reanalysis-based LRT are 30-40 hPa in the extratropics and 10-20 hPa in the tropics in comparison with radiosonde measurements.

This method of the LRT identification has been clarified in the main text.

The tick labels have been added in Fig. 1 as shown below.



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